Case Studies of Habitable Trojan Planets in the System of HD 23079

J. Eberle, M. Cuntz, B. Quarles, Z. E. Musielak

Department of Physics, University of Texas at Arlington, Box 19059, Arlington, TX 76019, USA

wjeberle@uta.edu, cuntz@uta.edu, billyq@uta.edu, zmusielak@uta.edu

ABSTRACT

We investigate the possibility of habitable Trojan planets in the HD 23079 star-planet system. This system consists of a solar-type star and a Jupiter-type planet, which orbits the star near the outer edge of the stellar habitable zone in an orbit of low eccentricity. We find that in agreement with previous studies Earth-mass habitable Trojan planets are possible in this system, although the success of staying within the zone of habitability is significantly affected by the orbital parameters of the giant planet and by the initial condition of the theoretical Earth-mass planet. In one of our simulations, the Earth-mass planet is captured by the giant planet and thus becomes a habitable moon.

Subject headings: extrasolar planets, habitable zone, orbital stability and planetary climate.

1. Introduction

The existence of planets in orbit about solar-type stars is now a well-established observational result. Obviously, the ultimate quest of these studies is to discover Earth-like planets located in the habitable zones (HZs) of their host stars. So far, a small number of super-Earth planets with masses of up to about 12 $M_\oplus$ (e.g., Udry *et al.* 2007; Vogt *et al.* 2010) have been found, typically located around M-type dwarf stars. Nevertheless, the existence of Earth-mass planets, including those hosted by solar-type stars, is strongly implied by various observational findings including the occurrence and mass distribution of close-in super-Earths, Neptunes, and Jupiters (Howard *et al.* 2010). Measurements by the authors indicate an increasing planet occurrence with decreasing planetary mass M_p akin to $M_p^{-0.48}$, implying that 23% of stars harbor a close-in Earth-mass planet (ranging from 0.5 to 2.0 $M_\oplus$);

see also Marcy & Butler (2000) for earlier results. Very recent support for the existence of Earth-type planets outside the Solar System is lent by the discovery of Kepler-10b, Kepler's first rocky planet with an estimated mass of 4.6 Earth masses (Batalha *et al.* 2011).

Long-term orbital stability of Earth-like planets in stellar HZs is necessary for the evolution of any form of life, particularly intelligent life. There is a large array of studies focusing on the orbital stability of hypothetical Earth-mass planets in stellar HZs concerning different types of host stars and star-planet configurations. Examples include studies by Gehman *et al.* (1996), Jones *et al.* (2001, 2005, 2006), Jones & Sleep (2010), Noble *et al.* (2002), Menou & Tabachnik (2003), Cuntz *et al.* (2003), von Bloh *et al.* (2003), and Asghari *et al.* (2004). Particular types of systems are those where a Jupiter-type planet orbits a star in the stellar HZ, therefore jeopardizing the possibility of habitable terrestrial planets in that system. This is actually the situation of HD 23079, the focus of the present paper.

Previously, Noble *et al.* (2002) investigated the orbital stability of terrestrial planets inside the HZs of 47 UMa and HD 210277. The center stars of these systems are very similar to the Sun concerning mass, spectral type, and effective temperature. Orbital stability was attained for the inner part of the HZ of 47 UMa; however, no orbital stability was found for hypothetical Earth-mass planets in the HZ of HD 210277. In this case, a Jupiter-type planet crosses the stellar HZ, thus effectively thwarting habitability for this system. Very recent examples were also given by Yeager *et al.* (2011) who studied the star-planet systems HD 20782 and HD 188015. In both cases, the giant planet significantly interferes with any Earth-mass planet in the stellar HZ assumed to have formed there for the sake of study. In all cases, the Earth-mass planet was ejected from the stellar HZ in a very short time.

However, if a giant planet is orbiting the star in the stellar HZ, there is still the principal possibility of habitable Trojan planets in those systems as pointed out by, e.g., Dvorak *et al.* (2004) and Schwarz *et al.* (2007). A Trojan planet is one located around one of the Lagrangian points L4 and L5 of the giant planet. These points lie on the giant planets orbit, ahead (L4) and behind (L5) the planet, each forming an equilateral triangle with the planet and its star. Thus, Trojan planets are also in a 1:1 resonance with the giant planet. Dvorak *et al.* (2004) investigated the stability regions of hypothetical terrestrial planets around L4 and L5 in specific systems, including HD 23079, in the framework of the restricted three body problem. They obtained relationships between the size of the stability regions and the orbital parameters of the giant planets, particularly its eccentricity. Studies about Neptune Trojans were given by, e.g., Dvorak *et al.* (2007).

A study by Schwarz *et al.* (2007) identified several exoplanetary systems that can harbour Trojan planets with stable orbits in the stellar HZs. Concerning HD 23079, this study concluded that a Trojan planet will only spend 35% of its time in the stellar HZ, assumed

to extend from 0.85 to 1.60 AU. In our study, however, we will consider a zone of habitability based on the generalized estimate by Underwood *et al.* (2003), implying habitability between 0.99 and 1.97 AU (see below). This means that the habitable area, which is the area of the stellar HZ annulus, is increased by 58% compared to that considered by Schwarz *et al.* (2007). In the present study, we will conclude that habitable Trojan planets are indeed possible in the system of HD 23079, although their existence is significantly affected by, e.g., the orbital parameters of the giant planet. Next we will describe our theoretical approach. We will discuss the adopted methods and the system parameters for HD 23079. Thereafter, we will describe our results. Finally, we will present our conclusions.

2. Theoretical Approach

2.1. Stellar and Planetary Parameters

HD 23079 has been monitored as part of the Anglo-Australian Planet Search (AAPS) program (Tinney *et al.* 2002) that is able to perform extrasolar planet detection and measurements with a long-term, systematic radial velocity precision of 3 m s^{-1} or better. HD 23079 was identified to host a Jupiter-type planet in a relatively large and nearly circular orbit. HD 23079 is an inactive main-sequence star; Gray *et al.* (2006) classified it as F9.5 V (see Table 1; all parameters have their usual meaning), an updated result compared to Houk & Cowley (1975) who found that HD 23079 is intermediate between an F8 and G0 star. Its stellar spectral type corresponds to a mass of $M = 1.10 \pm 0.15\ M_\odot$. The stellar effective temperature and radius are given as $T_{\rm eff} = 6030 \pm 52$ K and $R = 1.106 \pm 0.022\ R_\odot$, respectively (Ribas *et al.* 2003). Thus, HD 23079 is fairly similar to the Sun, though slightly hotter and slightly more massive. The detected planet (HD 23079 b) has a minimum mass of $M_p \sin i = 2.45 \pm 0.21\ M_J$. Furthermore, it has a semimajor axis of $a_p = 1.596 \pm 0.093$ AU and an eccentricity of $e_p = 0.102 \pm 0.031$ (Butler *et al.* 2006), corresponding to an orbital period of $P = 730.6 \pm 5.7$ days. The original results by Tinney *et al.* (2002) indicated very similar planetary parameters.

The orbital parameters of HD 23079 b are relatively similar to those of Mars, implying that HD 23079 b is orbiting its host star in or near the outskirts of the stellar HZ; see discussion below. The existence of HD 23079 b, a planet even more massive than Jupiter, makes it difficult for a terrestrial planet to orbit HD 23079 at a similar distance without being heavily affected by the giant planet; see results from previous case studies by Noble *et al.* (2002) and Yeager *et al.* (2011) who focused on the dynamics of HD 20782, HD 188015, and HD 210277. Concerning HD 23079, a previous investigation pertaining to habitable terrestrial Trojan planets was given by Dvorak *et al.* (2004).

2.2. Method of Integration

For our simulations of the HD 23079 system, we consider both the observed giant planet and a hypothetical terrestrial planet of one Earth-mass, i.e., $3.005 \times 10^{-6}\ M_\odot$, which allows us to execute a grid of model simulations. The method of integration uses a fourth-order Runge-Kutta integration scheme (Garcia 2000). The code has been extensively tested against known analytical solutions, including the two-body and restricted three-body problem (see Noble *et al.* 2002; Cuntz *et al.* 2007; Eberle *et al.* 2008, for detailed results). In the framework of our simulations that we limit to 10^6 yrs, we apply a time-step of 10^{-4} yrs for the integration scheme that is found to be fully appropriate. In that regard, we pursued test studies comparing the planetary orbits based on three different integration time-steps, which are: 10^{-3}, 10^{-4} and 10^{-5} yrs. In particular, we evaluated ΔR_{ij}, i.e., the magnitude of the difference between the position of the planet when different step sizes of 10^{-i} and 10^{-j} were used. We found that there is no significant change in outcome between models with time-steps of 10^{-4} and 10^{-5} yrs.

The initial conditions (i.e., starting velocities) for the orbits of the Earth-mass planets were chosen such that the planet was assumed to start at the midpoint of the stellar HZ (1.4779 AU) and to be in a circular orbit about the star, although it is evident that it will be significantly affected immediately by gravitational pull of the giant planet, which will prevent the planet from continuing a circular motion. For each set of models, defined by sets of values for the semimajor axis a_p and eccentricity e_p, given as 1.503, 1.596, 1.689 AU and 0.071, 0.102, 0.133, respectively, 8 different configurations are considered. They are defined by the 8 different starting (phase) angles for the Earth-mass planet, which are varied in increments of 45° noting that 0° corresponds to the 3 o'clock position. Moreover, the starting position of the Jupiter-type planet (HD 23079 b), for which we assume its minimum mass value of 2.45 M_J, was varied between its periastron and its apastron position. Therefore, a total of 144 initial configurations has been considered. Note that the Jupiter-type planet was always started at the 3 o'clock position, which after adjusting the orbital layout of the giant planet always coincided with its periastron (see Fig. 1) or apastron position depending on the type of model.

2.3. Stellar Habitable Zone

The extent of the HZ of HD 23079 has been calculated following the formalism by Underwood *et al.* (2003) based on previous work by Kasting *et al.* (1993). Underwood *et al.* (2003) supplied a polynomial fit depending on the stellar luminosity and the stellar effective temperature that allows to calculate the extent of the conservative and the generalized HZ.

Noting that HD 23079 is more luminous than the Sun, it is expected that its HZ is more extended than the solar HZ, for which the inner and outer limit of the generalized HZ were given as 0.84 and 1.67 AU, respectively (Kasting *et al.* 1993). The generalized HZ is defined as bordered by the runaway greenhouse effect (inner limit), where water vapour enhances the greenhous effect thus leading to runaway surface warming, and by the maximum greenhouse effect (outer limit), where a surface temperature of 273 K can still be maintained by a cloud-free CO_2 atmosphere. The inner limit of the conservative HZ is defined by the onset of water loss, i.e., the atmosphere is warm enough to allow for a wet stratosphere from where water is gradually lost by photodissociation and subsequent hydrogen loss to space. Furthermore, the outer limit of the conservative HZ is defined by the first CO_2 condensation attained by the onset of formation of CO_2 clouds at a temperature of 273 K.

For HD 23079, the limits of the conservative HZ are given as 1.1378 and 1.6362 AU, whereas the limits of generalized HZ are given as 0.9896 and 1.9662 AU (see Fig. 1). The limits of the generalized HZ are those employed in our numerical planetary studies[1]. The underlying definition of habitability is based on the assumption that liquid surface water is a prerequisite for life, a key concept that is also the basis of ongoing and future searches for extrasolar habitable planets (e.g., Catanzarite *et al.* 2006; Cockell *et al.* 2009). The numerical evaluation of these limits is based on an Earth-type planet with a $CO_2/H_2O/N_2$ atmosphere. Specifically, the inner limit of habitability is set by the loss of water from the upper planetary atmosphere through photodissociation and subsequent escape of hydrogen to space associated with a run-away greenhouse effect. The outer limit of habitability is given by the maximum greenhouse effect (Kasting *et al.* 1993; Underwood *et al.* 2003), by which a surface temperature of 273 K can be maintained by a cloud-free CO_2 atmosphere.

We point out that concerning the outer edge of habitability, even less conservative limits have been proposed in the meantime (e.g., Forget & Pierrehumbert 1997; Mischna *et al.* 2000). They are based on the assumption of relatively thick planetary CO_2 atmospheres and invoke strong backwarming that may further be enhanced by the presence of CO_2 crystals and clouds. However, as these limits, which can be as large as 2.4 AU in case of the Sun, depend on distinct properties of the planetary atmosphere, they are not relevant for our study. Nevertheless, we convey this type of limit for the sake of curiosity (see Fig. 1), noting that it has properly been adjusted to 2.75 AU in consideration of the radiative conditions of the planetary host star, HD 23079. Moreover, the significance of this extreme limit has recently been challenged based on detailed radiative transfer simulations (Halevy *et al.* 2009).

---

[1]The physical limits of habitability are much less stringent than implied by the numerical precision of these values; nevertheless, these values were used for checking if the Earth-mass planet has left the stellar HZ.

3. Results and Discussion

3.1. Case Studies of Habitable Trojan Planets

Table 2 and Table 3 summarize the time the Earth-mass planet remains within the stellar HZ, i.e., before exiting the stellar HZ or being permanently ejected from the system. Of the 144 total considered initial configurations 13 survived at least 1 million years, 93 crossed the upper limit of the HZ, 28 crossed the lower limit of the HZ, and 10 collided or may have had a very close approach with the giant planet. Some of those who crossed the HZ at the lower or upper limit as first exit from the HZ may have had a very close approach with the giant planet, resulting in destruction while entering the Roche limit (Williams 2003) or in a collision with the giant planet, at a later time. Of the 13 survivors, 12 are Trojan types, that is they exist in stable orbits around the equilateral equilibrium positions much like that demonstrated in Dvorak *et al.* (2004).

In the cases where the giant planet is initially in the periastron position, only models with the smallest considered semimajor axis and eccentricity combination, which are a_p = 1.503 AU and $e_p = 0.071$, result in habitable Trojan planets (see Fig. 2). In this case, four different starting positions (phase angles) appear to be consistent with long-term stability (see Table 2). It is clear that the Earth-mass planet is safely inside of the stellar HZ but it is a snug fit. For the next larger eccentricity considered, which is 0.102, there are various cases where the Earth-mass planet stays within the HZ for some hundreds thousand years before finally crossing the upper limit of the HZ. When the eccentricity of the giant planet is increased to 0.133, the Earth-mass planet remains within the HZ at best for only a few hundred years.

The situation is, in principle, similar for the cases where the giant planet is initially placed at the apastron position. In this case, for $a_p = 1.503$ AU, the Earth-mass planet remained in the stellar HZ for at least a million years for two eccentricity simulations, which are $e_p = 0.071$ and 0.102 (see Figs. 3 and 4, respectively). Comparing Fig. 4 to Fig. 3, it is clear that the Earth-mass planet moves in a wider area and approaches the edges of the HZ for the larger eccentricity, thus illustrating how the planet remained in the HZ for such a long time before exiting in the periastron case with the same parameters. In some of those latter cases, we found that the planet was outside the HZ for a brief time (i.e., considerably less than a planetary orbit), but most likely without losing its habitability. This conclusion is motivated by the previous study of Williams & Pollard (2002) that showed that brief excursions from the HZ are insufficient to nullify planetary habitability because the latter is expected to mainly depend on the average stellar flux received over an entire orbit, rather than the length of the time spent within the HZ.

Note that Figs. 2 and 3 display models of orbital stability for the Earth-mass planet in a synodic (rotating) coordinate system. Thus, the "banana-shaped" areas correspond to the domains about L4 or L5, where stability for the Earth-mass planet is encountered. The thin line at the 3 o'clock position corresponds to the motion of the giant planet due to its slightly elliptical orbit. Clearly, only Earth-mass planets placed at phase angles of 45°, 90°, 270°, and 315° have a reasonable chance to develop into Trojan planets, whereas for other starting angles ejections from the HZ, and usually also from the star-planet system, will occur due to gravitational interaction with the giant planet. If the Earth-mass planet was initially placed at an angle of 60° or 300°, it can be expected that it will continue to remain a Trojan planet.

For the sake of curiosity, we also evaluated various cases where the Earth-mass planet never had a chance of becoming habitable. Hence, we chose five cases of different semimajor axes and eccentricities for the giant planet. In all cases the giant planet started at the periastron position and the initial phase angle of the Earth-mass planet was chosen as 180°. The simulations are depicted in Fig. 5. In Fig. 5a, with $a_p = 1.503$ AU and $e_p = 0.102$, the system experiences a relatively long period during which the Earth-mass planet first exits the HZ at 48.4 yrs. This event is preceded by a close approach with the giant planet. The simulation is terminated at 195.9 yrs due to an expected collision with the giant planet.

Figures 5b to 5d are all based on $a_p = 1.596$ AU, but the depicted simulations assume different eccentricities for the giant planet, which are $e_p = 0.071$, 0.102, and 0.133, respectively. In Fig. 5b, the system experiences a short period during which the Earth-mass planet first exits the HZ at 7.93 yrs. This event is again preceded by a close approach with the giant planet. The simulation is terminated at 9112 yrs due to the expected collision with the giant planet. In Fig. 5c, the system experiences a short period during which the Earth-mass planet first exits the HZ at 7.80 yrs. This event is preceded by a close approach with the giant planet. The simulation is terminated at 13400 yrs considering that the Earth-mass planet is ejected from the system. Habitability is ultimately prevented as the Earth-mass planet becomes "free-floating". Free-floating planets have previously been observed in case of the Trapezium cluster (Lucas & Roche 2000); note that planetary ejections due to orbital instabilities are an important candidate process for this finding.

In Fig. 5d, with $a_p = 1.596$ AU and $e_p = 0.133$, this system experiences a short period during which the Earth-mass planet first exits the HZ at 7.82 yrs. It is reentering and exiting the HZ several times. However, the simulation is terminated at 54.60 yrs due to an expected collision with the giant planet. In case of Fig. 5e, with $a_p = 1.689$ AU and $e_p = 0.102$, the system again experiences a short period during which the Earth-mass planet first exits the HZ at 4.78 yrs. This event is preceded by a close approach with the giant planet. Eventually, the planet also becomes free-floating; the simulation is terminated at about 7×10^4 yrs. Figure

5a and 5d show oscillatory behaviours regarding the orbital motion of the Earth-mass planet. Noting that the Earth-mass planet starts at a phase angle of 180°, it initially orbits the star. However, when it approaches the giant planet, its orbit is being perturbed causing the loops. Thus, the Earth-mass planet exits and re-enters the HZ multiple times until the end of the simulation.

3.2. On the Possibility of Habitable Moons

Our set of model simulations reveal a considerable variety in the dynamics of the Earth-mass planet. The most surprising case is the following: For $a_p = 1.596$ AU and $e_p = 0.133$ (see Fig. 6) with the Jupiter-type planet initially placed at periastron position and the Earth-mass planet placed at 0°, it was found that the latter never crosses the inner or outer limit of the stellar HZ during the simulation time of 10^6 years. However, it is found to orbit the giant planet in a retrograde orbit (relative to the orbital motion of the giant planet about the star). In this case, the Earth-mass planet is captured by the giant planet and becomes a habitable moon, which occurs almost immediately after the start of the simulation.

The analysis of its orbital data shows that the moon's semimajor axis concerning its motion about the giant planet is $a_{\rm moon} \simeq 0.051$ AU. Its eccentricity is $e_{\rm moon} \simeq 0.8$ entailing a perigee and apogee of 0.0034 and 0.098 AU, respectively. Thus, with a uniform data sampling rate, the moon is most likely to be recorded at or near apogee. From Fig. 7 it is evident that there is also a precession of the perigee in a retrograde sense with a period of approximately 30 years. Figure 8 shows two histograms regarding the time-dependent distance of the moon from the giant planet, which reconfirms the moon's highly eccentric orbit. The existence of a habitable moon in the HD 23079 system is also consistent with the criterion of Hill stability as pointed out by, e.g., Donnison (2010). This study explores dynamic Hill stability for a large variety of three-body systems considering moon/planet mass ratios of 0.1, 0.01 and 0.001.

There is a persistent interest in the study of habitable moons with respect to extrasolar giant planets orbiting host stars in the stellar HZs. Previous studies of habitable moons in systems akin to HD 23079 have been given by Williams *et al.* (1997), Barnes & O'Brien (2002), and others. The study by Williams *et al.* (1997) did not include HD 23079b as this star-planet system was unknown at the time when this study was pursued. However, by targeting the companions of 16 Cyg B and 47 UMa, Williams *et al.* (1997) investigated appropriate orbital parameters of possible moons, and pointed out that the moons need to be large enough (i.e., $> 0.12\ M_\oplus$) to retain a substantial and long-lived atmosphere, and furthermore would need to possess a significant magnetic field to prevent its atmosphere

from being sputtered away by the ongoing bombardment of energetic ions from the planet's magnetosphere, if existing. Another study of possible moons, which is fully applicable to the HD 23079 star-planet system, has been given by Barnes & O'Brien (2002). They concluded that Earth-like moons of a Jovian planet like HD 23079b would be able to exist for at least 5 Gyr considering that the stellar mass of HD 23079 exceeds 0.15 $M_{\odot}$.

4. Conclusions

The aim of our study was to add to the investigation of habitable Trojan planets in the HD 23079 star-planet system. This system consists of a main-sequence star slightly hotter than the Sun. Additionally, it contains a Jupiter-type planet with a minimum mass of 2.45 M_J that is orbiting the star in a slightly elliptical orbit that is positioned within the stellar HZ. The main goal of our study was to explore if Earth-mass habitable Trojan planets can exist in this system.

As the centerpiece of our study, we calculated a total of 144 orbital stability simulations for the Earth-mass planet by choosing different starting positions (phase angle) as well as placing the Jupiter-type planet either at periastron or apastron position. The attainment of habitability solutions was found to critically depend on various parameters, which include the orbital parameters of the giant planet (semi-major axis, eccentricity) and the initial condition (phase angle) of the theoretical Earth-mass planet. We encoutered a variety of different outcomes, which include (1) ejection of the Earth-mass planet from the system, (2) engulfment of the planet by the star (or possible destruction in accord with the Roche limit criterion), (3) capture of the planet, thus becoming an habitable moon, or (4) remaining within the stellar HZ. The latter case was only attained in models where the orbit of the giant planet had a relatively low eccentricity (but still within its observationally given uncertainty), which however may be partially due to the implemented choice of planetary starting positions. Concerning the latter case, there were also cases (not shown in detail) where the planet took short-term excursions from the HZ (i.e., considerably less than the orbital period of HD 23079b, which is about 730 d), which should be insufficient to nullify its habitability because the latter is expected to mainly depend on the average stellar flux received over an entire orbit, rather than the length of the time spent within the HZ (Williams & Pollard 2002), although the ultimate effect of temporarily leaving the zone of habitability will still partially depend on the atmospheric thickness, structure and composition (e.g., Dressing *et al.* 2010).

Moreover, we note that our study is supplementing previous work by Schwarz *et al.* (2007) who concluded that a Trojan planet in the HD 23079 star-planet system will only

spend 35% of its time in the stellar HZ. However, this estimation was based on a considerably narrower zone of habitability than used in the present study. Another, albeit minor, difference is that Schwarz *et al.* (2007) used slightly different orbital parameters for HD 23079b than in the current study. In conclusion, it can be argued that the system of HD 23079 is very well suited for the existence of habitable Earth-type Trojan planets, and thus deserves serious consideration in ongoing and future planetary search missions.

Acknowledgements

This work has been supported by the U.S. Department of Education under GAANN Grant No. P200A090284 (J. E. and B. Q.), the SETI institute (M. C.) and the Alexander von Humboldt Foundation (Z. E. M.).

REFERENCES

Asghari, N. *et al.* (2004). *Astron. Astrophys.* **426**, 353–365.

Barnes, J.W. & O'Brien, D.P. (2002). *Astrophys. J.* **575**, 1087–1093.

Batalha, N.M. *et al.* (2011). *Astrophys. J.*, **729**, 27.

Butler, R.P. *et al.* (2006). *Astrophys. J.* **646**, 505–522.

Catanzarite, J., Shao, M., Tanner, A., Unwin, S. & Yu, J. (2006). *Publ. Astron. Soc. Pacific* **118**, 1319–1339.

Cockell, C.S. *et al.* (2009). *Astrobiology* **9**, 1–22.

Cuntz, M., von Bloh, W., Bounama, C. & Franck, S. (2003). *Icarus* **162**, 214–221.

Cuntz, M., Eberle, J. & Musielak, Z.E. (2007). *Astrophys. J. Lett.* **669**, L105–L108.

Dressing, C.D., Spiegel, D.S., Scharf, C.A., Menou, K. & Raymond, S.N. (2010). *Astrophys. J.* **721**, 1295–1307.

Donnison, J.R. (2010). *Mon. Not. Roy. Astron. Soc.* **406**, 1918–1934.

Dvorak, R., Pilat-Lohinger, E., Schwarz, R. & Freistetter, F. (2004). *Astron. Astrophys.* **426**, L37–L40.

Dvorak, R., Schwarz, R., Sűli, Á. & Kotoulas, T. (2007). *Mon. Not. Roy. Astron. Soc.* **382**, 1324–1330.

Eberle, J., Cuntz, M. & Musielak, Z.E. (2008). *Astron. Astrophys.* **489**, 1329–1335.

European Space Agency (1997). The Hipparcos and Tycho Catalogues (SP-1200) ESA, Noordwijk.

Forget, F. & Pierrehumbert, R.T. (1997). *Science* **278**, 1273–1276.

Garcia, A.L. (2000). *Numerical Methods for Physics*, 2nd edn. Prentice Hall, Upper Saddle River.

Gehman, C.S., Adams, F.C. & Laughlin, G. (1996). *Publ. Astron. Soc. Pacific* **108**, 1018–1023.

Gray, R.O., Corbally, C.J., Garrison, R.F., McFadden, M.T., Bubar, E.J., McGahee, C.E., O'Donoghue, A.A. & Knox, E.R. (2006). *Astron. J.* **132**, 161–170.

Halevy, I., Pierrehumbert, R.T. & Schrag, D.P. (2009). *J. Geophys. Res.* **114**, D18112.

Howard, A.W., Marcy, G.W., Johnson, J.A., Fischer, D.A., Wright, J.T., Isaacson, H., Valenti, J.A., Anderson, J., Lin, D.N.C. & Ida, S. (2010). *Science* **330**, 653–655.

Houk, N. & Cowley, A.P. (1975). *Michigan Catalog of Two-Dimensional Spectral Types for the HD Stars*, Vol. 1, University of Michigan, Ann Arbor.

Jones, B.W. & Sleep, P.N. (2010). *Mon. Not. Roy. Astron. Soc.* **407**, 1259–1267.

Jones, B.W., Sleep, P.N. & Chambers, J.E. (2001). *Astron. Astrophys.* **366**, 254–262.

Jones, B.W., Underwood, D.R. & Sleep, P.N. (2005). *Astrophys. J.* **622**, 1091–1101.

Jones, B.W., Sleep, P.N. & Underwood, D.R. (2006). *Astrophys. J.* **649**, 1010–1019.

Kasting, J.F., Whitmire, D.P. & Reynolds, R.T. (1993). *Icarus* **101**, 108–128.

Lucas, P.W. & Roche P.F. (2000). *Mon. Not. Roy. Astron. Soc.* **314**, 858–864.

Marcy, G.W. & Butler R.P. (2000). *Publ. Astron. Soc. Pacific* **112**, 137–140.

Menou, K. & Tabachnik, S. (2003). *Astrophys. J.* **583**, 473–488.

Mischna, M.A., Kasting, J.F., Pavlov, A. & Freedman, R. (2000). *Icarus* **145**, 546–554.

Noble, M., Musielak, Z.E. & Cuntz, M. (2002). *Astrophys. J.* **572**, 1024–1030.

Ribas, I., Solano, E., Masana, E. & Giménez, A. (2003). *Astron. Astrophys.* **411**, L501–L504.

Schwarz, R., Dvorak, R., Sűli, Á. & Érdi, B. (2007). *Astron. Astrophys.* **474**, 1023–1029.

Tinney, C.G., Butler, R.P., Marcy, G.W., Jones, H.R.A., Penny, A.J., McCarthy, C. & Carter, B.D. (2002). *Astrophys. J.* **571**, 528–531.

Udry, S., Bonfils, X., Delfosse, X., Forveille, T., Mayor, M., Perrier, C., Bouchy, F., Lovis, C., Pepe, F., Queloz, D. & Bertaux, J.-L. (2007). *Astron. Astrophys.* **469**, L43–L47.

Underwood, D.R., Jones, B.W. & Sleep, P.N. (2003). *Int. J. Astrobiol.* **2**, 289–299.

Vogt, S.S., Butler, R.P., Rivera, E.J., Haghighipour, N., Henry, G.W. & Williamson, M.H. (2010). *Astrophys. J.* **723**, 954–965.

von Bloh, W., Cuntz, M., Franck, S. & Bounama, C. (2003). *Astrobiology* **3**, 681–688.

Williams, I.P. (2003). *Celest. Mech. Dyn. Astron.* **87**, 13–25.

Williams, D.M., Kasting, J.F. & Wade, R.A. (1997). *Nature* **385**, 234–236.

Williams, D.M. & Pollard, D. (2002). *Int. J. Astrobiol.* **1**, 61–69.

Yeager, K.E., Eberle, J. & Cuntz, M. (2011). *Int. J. Astrobiol.* **10**, 1–13.

This preprint was prepared with the AAS LaTeX macros v5.0.

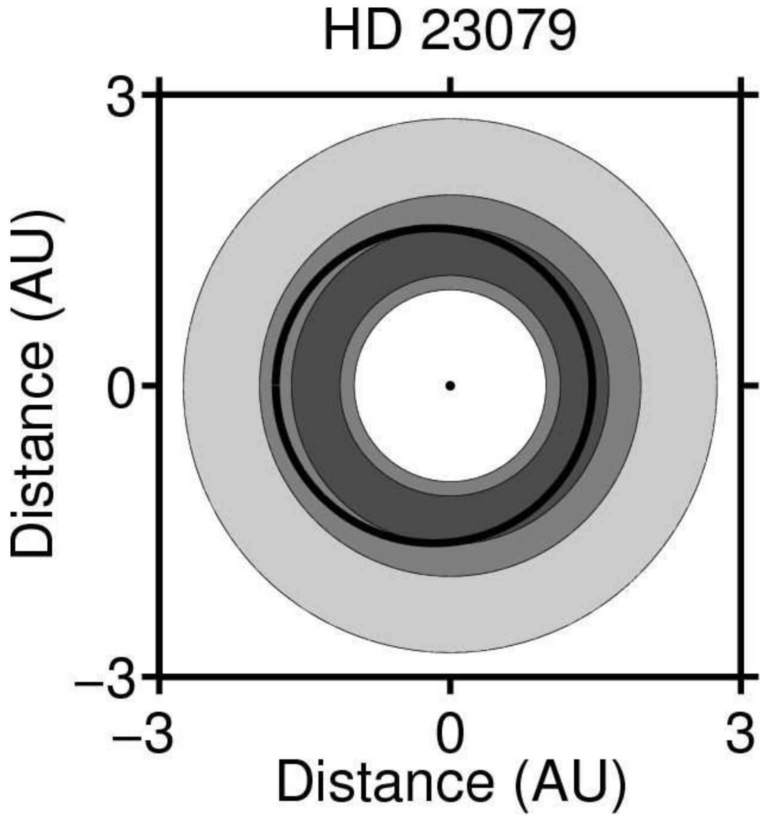

Fig. 1.— Extent of the HZ for HD 23079, defined by its conservative limits (dark grey) and generalized limits (medium grey). In addition, we depict the outer limit of an extreme version of the generalized HZ (light grey) following the work by Mischna *et al.* (2000), although this limit may be unrealistic based on subsequent studies. The orbit of HD 23079 b, a Jupiter-type giant planet, is depicted by a thick solid line.

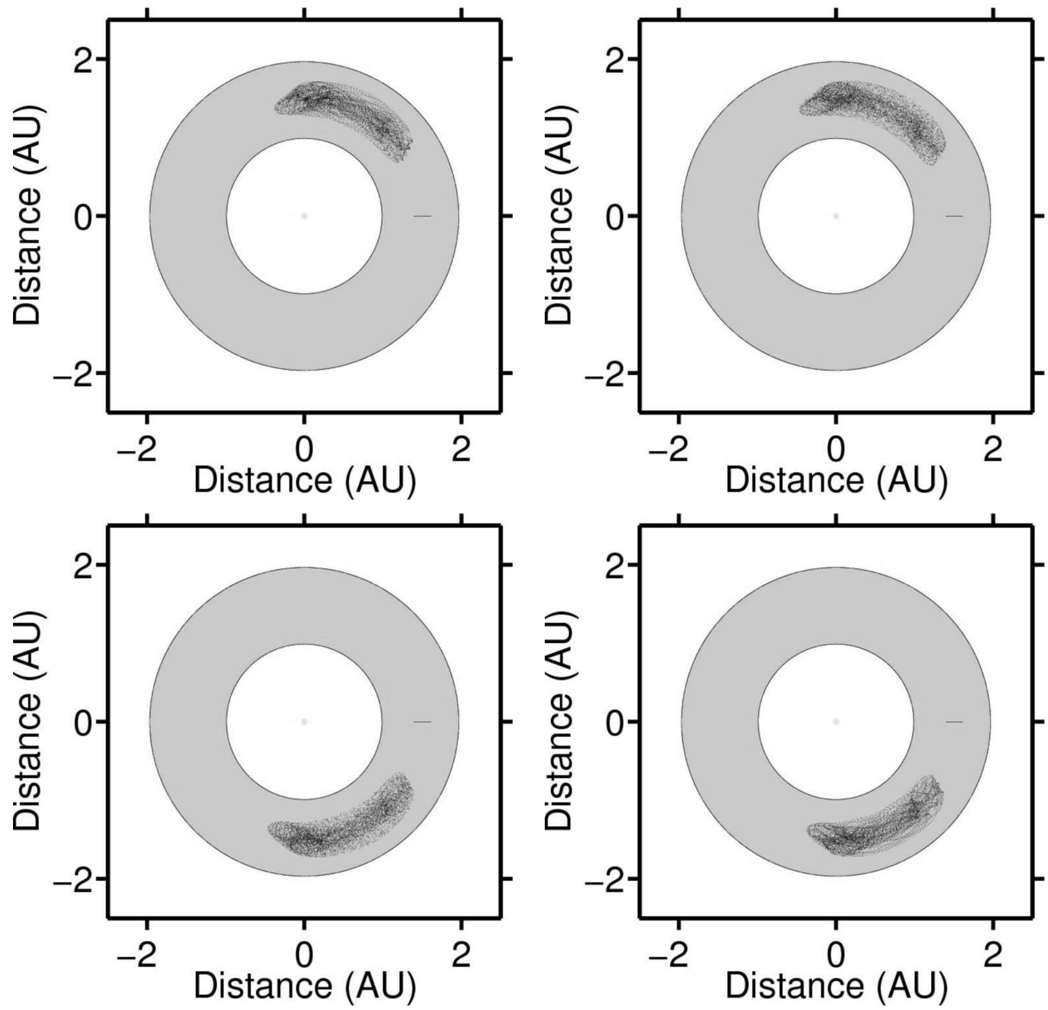

Fig. 2.— Orbital stability simulations with HD 23079 b initially placed at periastron with a_p = 1.503 AU, e_p = 0.071 and the Earth-mass planets placed at four different starting angles, which are: 45° (top left), 90° (top right), 270° (bottom left), and 315° (bottom right). Using a rotating coordinate system, HD 23079 b moves along the thin line. The Earth-mass Trojan planets, which give rise to the "banana-shaped" area at L4 or L5, remain within the HZ for at least 10^6 years.

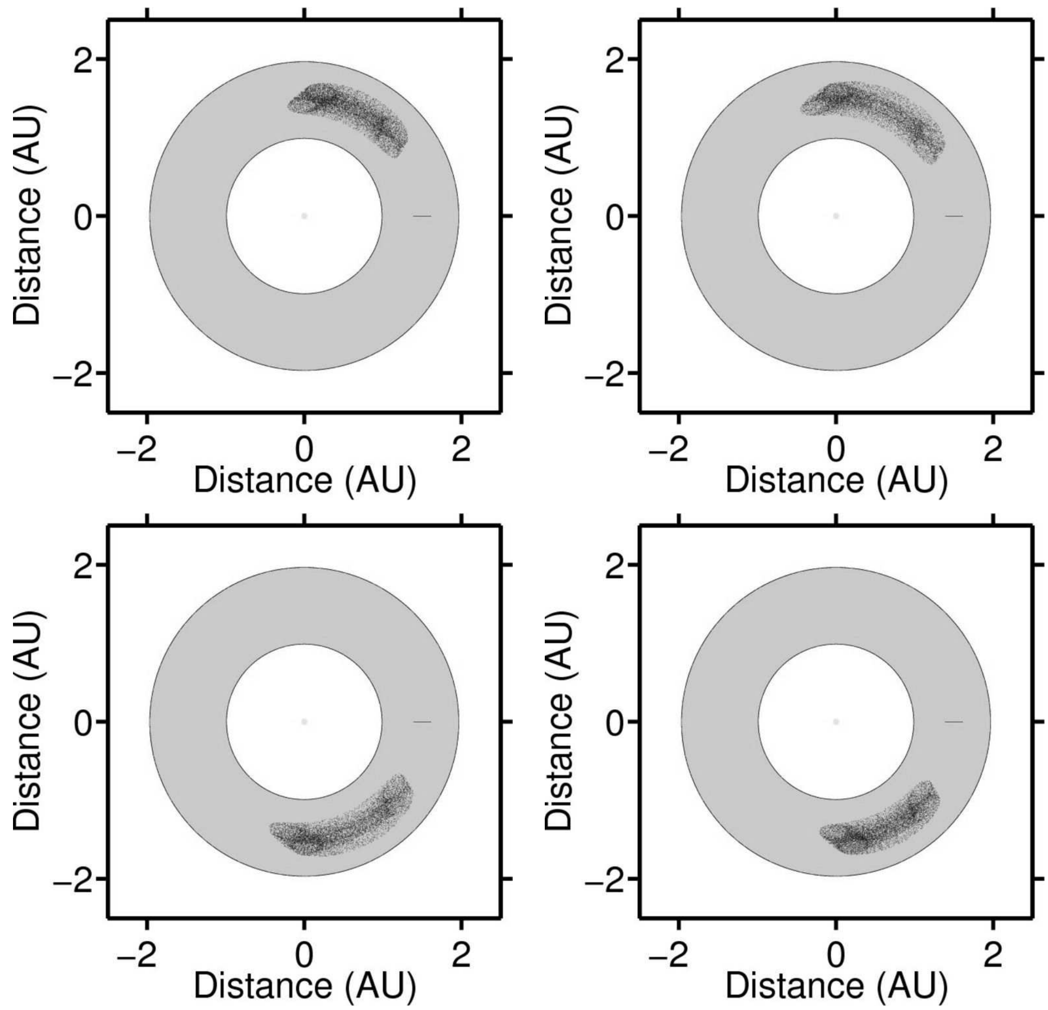

Fig. 3.— Orbital stability simulations with HD 23079 b initially placed at apastron with a_p = 1.503 AU, e_p = 0.071 and the Earth-mass planets placed at four different starting angles, which are: 45° (top left), 90° (top right), 270° (bottom left), and 315° (bottom right). Using a rotating coordinate system, HD 23079 b moves along the thin line. The Earth-mass Trojan planets, which give rise to the "banana-shaped" area at L4 or L5, remain within the HZ for at least 10^6 years.

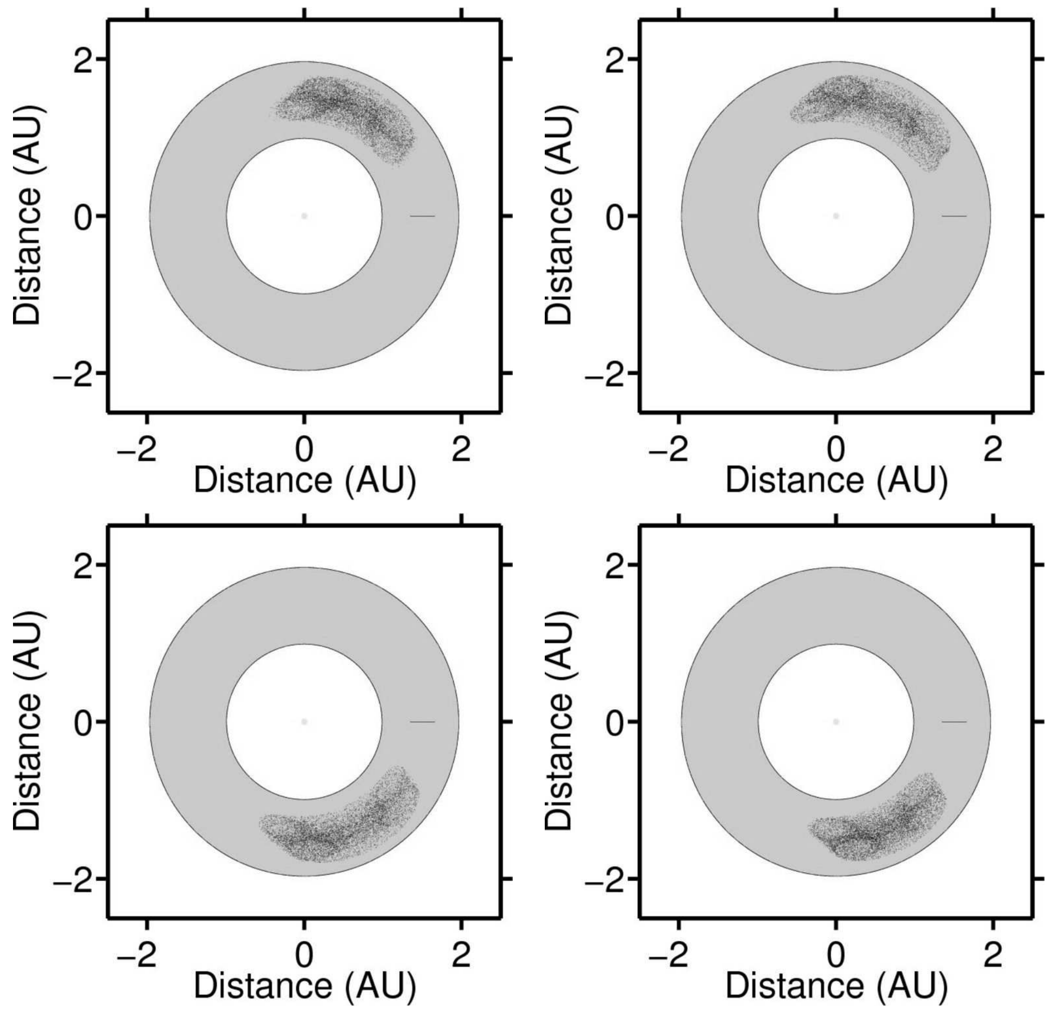

Fig. 4.— Orbital stability simulations with HD 23079 b initially placed at apastron with a_p = 1.503 AU, $e_p = 0.102$ and the Earth-mass planets placed at four different starting angles, which are: 45° (top left), 90° (top right), 270° (bottom left), and 315° (bottom right). Using a rotating coordinate system, HD 23079 b moves along the thin line. The Earth-mass Trojan planets, which give rise to the "banana-shaped" area at L4 or L5, remain within the HZ for at least 10^6 years.

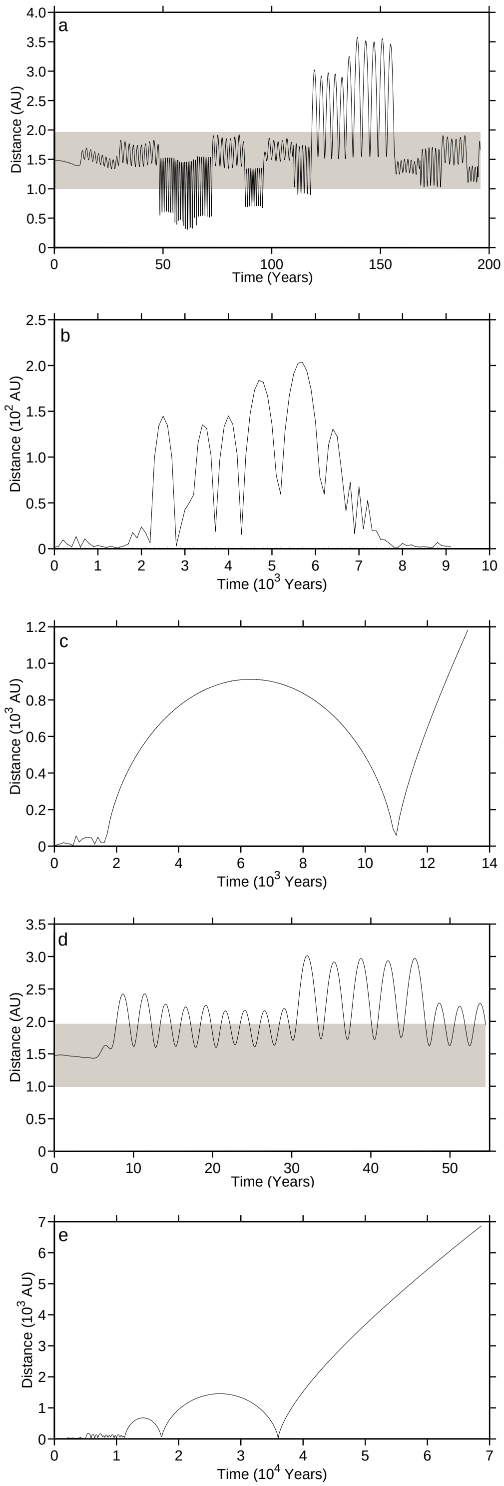

Fig. 5.— Orbital stability simulations with HD 23079 b initially placed at periastron for Earth-mass planets placed at starting angles of 180°. The model simulations differ regarding the selected values for the orbital parameters a_p and e_p of the giant planet HD 23079 b (see also Table 2 for further information). The respective value pairs (a_p, e_p) are: (1.503, 0.102), (1.596, 0.071), (1.596, 0.102), (1.596, 0.133), and (1.689, 0.102) for panel *a*, *b*, *c*, *d*, and *e*, respectively, with a_p in AU. The grey domains (only visible in panel *a* and *d*) depict HD 23079's stellar HZ; see Table 2 for the times of first exit of the planet from the HZ. Note

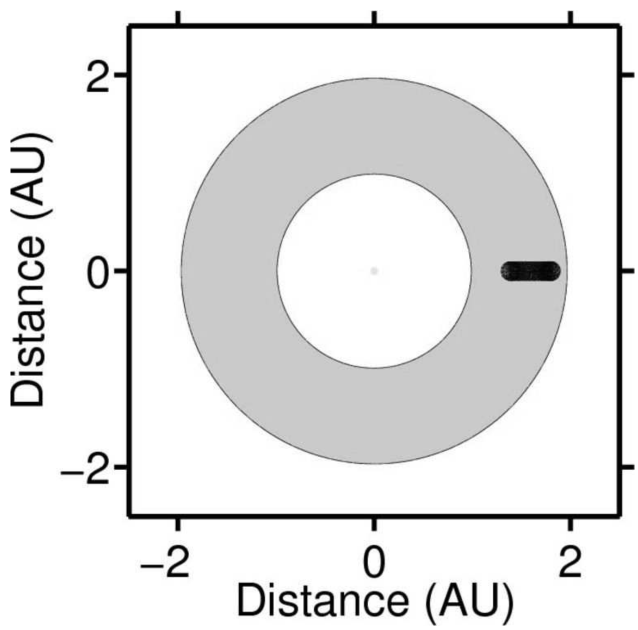

Fig. 6.— Orbital stability simulations with HD 23079 b initially placed at periastron with a_p = 1.596 AU, e_p = 0.133 and the Earth-mass planets placed at a starting angle of 0°. The Earth-mass planet remains within the HZ for at least 10^6 years. However, during that time it was captured by the giant planet and thus became a natural satellite (moon) of that planet, resulting in the small black area. Also note the absence of the "banana-shaped" area at L4 or L5.

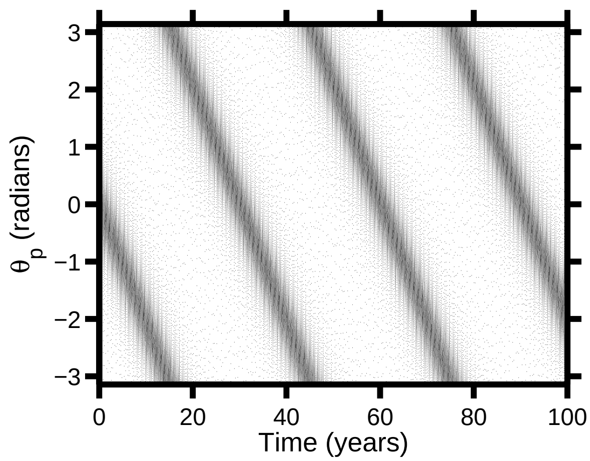

Fig. 7.— Using the giant planet as reference and origin of the coordinate system, we measure the angle θ_p of the captured terrestrial planet, which thus became a moon, in a sidereal frame (with $\theta_p = 0$ corresponding to the 3 o'clock position). With a uniform data sampling rate, the moon will be more likely recorded at or near apogee. Since the orbit of the moon is highly eccentric, there are many more points when the moon is near apogee compared to when it is near perigee.

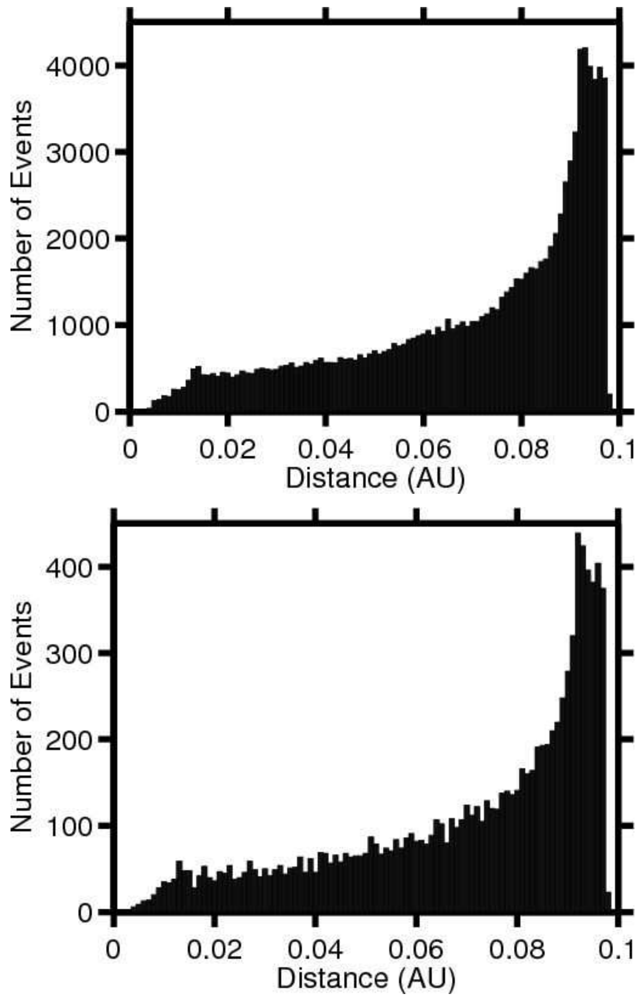

Fig. 8.— Histogram displaying the time-dependent distance between the moon and the giant planet. Top: Simulation with an elapsed time of 1000 years and a data sampling period of 0.01 years. Bottom: Simulation with an elapsed time of 1×10^6 years and a data sampling period of 100 years. The comparison between both figures shows that there is little, if any, evolution of the system over the total time of simulation.

Table 1. Stellar and Planetary Parameters

Parameter	Value	Reference
Spectral Type	F9.5 V	Gray *et al.* (2006)
RA	3 39 43.0952	ESA (1997)[a,b]
DEC	− 52 54 57.017	ESA (1997)[a,b]
$T_{\rm eff}$ (K)	6030 ± 52	Ribas *et al.* (2003)
R ($R_\odot$)	1.106 ± 0.022	Ribas *et al.* (2003)
M ($M_\odot$)	1.10 ± 0.15	[c]
M_V	4.42 ± 0.05	ESA (1997)[a,b,d]
$M_{\rm bol}$	4.25 ± 0.05	ESA (1997)[a,b,d]
Distance (pc)	34.60 ± 0.67	ESA (1997)[a,b,d]
$M_p$sin$i$ (M_J)	2.45 ± 0.21	Butler *et al.* (2006)
P (days)	730.6 ± 5.7	Butler *et al.* (2006)
a_p (AU)	1.596 ± 0.093	Butler *et al.* (2006)
e_p	0.102 ± 0.031	Butler *et al.* (2006)

Note. — [a]data from SIMBAD, see `http://simbad.u-strasbg.fr`
[b]adopted from the *Hipparcos* catalogue
[c]based on spectral type
[d]based on parallax 28.90 ± 0.56 mas

Table 2. Time of First Exit (or Ejection) of the Earth-Mass Planet from the HZ (in years)

a_p (AU)	e_p ...	0° ...	45° ...	90° ...	135° ...	180° ...	225° ...	270° ...	315° ...
1.503	0.071	3.26E−01 U	...	...	1.67E+02 L	1.05E+02 L	5.38E+01 L	...	...
1.503	0.102	1.84E+00 C	2.30E+05 U	7.09E+05 U	8.51E+01 U	4.84E+01 L	4.27E+01 U	8.78E+05 U	2.59E+05 U
1.503	0.133	1.07E+00 L	3.46E+02 L	6.13E+02 L	9.72E+01 U	6.04E+01 U	4.30E+01 U	4.78E+02 U	1.85E+03 U
1.596	0.071	1.30E−03 C	2.33E+02 U	1.54E+01 U	9.48E+00 U	7.93E+00 U	5.59E+00 U	3.89E+00 U	1.95E+00 U
1.596	0.102	4.83E−01 U	1.53E+01 U	1.53E+01 U	1.23E+01 U	7.80E+00 U	5.56E+00 U	3.73E+00 U	1.77E+00 U
1.596	0.133	...	3.38E+01 L	1.52E+01 U	9.48E+00 L	7.82E+00 U	6.02E+00 U	3.90E+00 U	1.42E+00 C
1.689	0.071	1.09E−01 C	8.47E+00 U	8.99E+00 U	7.25E+00 L	4.86E+00 U	4.05E+00 U	2.64E+00 U	3.90E+01 L
1.689	0.102	2.85E−02 C	8.02E+00 C	8.56E+00 L	6.73E+00 U	4.78E+00 U	4.38E+00 L	2.45E+00 U	2.18E+00 L
1.689	0.133	5.90E−03 C	8.93E+00 U	1.91E+01 U	6.55E+00 L	4.59E+00 U	8.97E+00 U	2.23E+00 U	8.13E+00 U

Note. — The total time of simulation is 10^6 yrs. The Jupiter-type planet started at the periastron position and the initial velocity of the Earth-mass planet was computed to begin a circular motion about the star. U means that the Earth-mass planet crosses the upper limit of the HZ given as 1.9662 AU; whereas L means that the Earth-mass planet crosses the lower limit of the HZ given as 0.9896 AU. C means that the Earth-mass planet has a close encounter with the giant planet, possibly resulting in a collision; therefore, the simulation was discontinued. If no data are given, the simulation lasted beyond 10^6 yrs without exiting the HZ.

Table 3. Time of First Exit (or Ejection) of the Earth-Mass Planet from the HZ (in years)

a_p (AU)	e_p ...	0° ...	45° ...	90° ...	135° ...	180° ...	225° ...	270° ...	315° ...
1.503	0.071	8.50E−01 U	...	...	2.95E+01 U	5.08E+01 L	4.01E+01 U	...	...
1.503	0.102	1.45E+00 U	...	...	9.94E+01 L	2.32E+01 L	2.11E+01 U	..	...
1.503	0.133	9.33E−01 L	1.28E+03 L	1.46E+03 U	2.54E+01 L	4.99E+01 U	8.52E+00 U	4.19E+03 U	7.58E+02 U
1.596	0.071	7.07E+00 L	2.57E+02 U	3.27E+01 L	5.60E+01 C	6.61E+00 U	4.97E+00 U	2.86E+01 U	4.18E+01 U
1.596	0.102	1.33E+01 U	3.44E+01 U	5.33E+01 U	5.34E+01 U	6.24E+00 C	4.77E+00 U	6.49E+01 U	2.44E+01 U
1.596	0.133	7.07E+00 U	2.05E+01 U	7.08E+01 U	3.23E+01 U	1.73E+01 U	5.07E+00 U	2.26E+01 U	2.08E+01 U
1.689	0.071	1.89E+01 C	3.61E+01 U	7.76E+00 U	6.45E+00 U	5.17E+00 U	3.61E+00 U	3.61E+00 U	1.38E+00 U
1.689	0.102	7.48E+00 L	1.00E+01 U	7.59E+00 U	7.32E+00 U	5.52E+00 L	3.46E+00 U	3.32E+00 U	1.23E+00 U
1.689	0.133	1.87E+01 U	9.64E+00 U	7.41E+00 U	7.02E+00 L	5.53E+01 L	3.27E+00 U	3.44E+00 L	1.08E+00 U

Note. — The total time of simulation is 10^6 yrs. The Jupiter-type planet started at the apastron position and the initial velocity of the Earth-mass planet was computed to begin a circular motion about the star. For further information see notes of Table 2.